 DOI: 10.1111/j.1539-6924.2010.01524.x

Modeled Estimates of Soil and Dust Ingestion Rates for Children

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Daily soil/dust ingestion rates typically used in exposure and risk assessments are based on tracer element studies, which have a number of limitations and do not separate contributions from soil and dust. This article presents an alternate approach of modeling soil and dust ingestion via hand and object mouthing of children, using EPA's SHEDS model. Results for children 3 to <6 years old show that mean and 95th percentile total ingestion of soil and dust values are 68 and 224 mg/day, respectively; mean from soil ingestion, hand-to-mouth dust ingestion, and object-to-mouth dust ingestion are 41 mg/day, 20 mg/day, and 7 mg/day, respectively. In general, hand-to-mouth soil ingestion was the most important pathway, followed by hand-to-mouth dust ingestion, then object-to-mouth dust ingestion. The variability results are most sensitive to inputs on surface loadings, soil-skin adherence, hand mouthing frequency, and hand washing frequency. The predicted total soil and dust ingestion fits a lognormal distribution with geometric mean = 35.7 and geometric standard deviation = 3.3. There are two uncertainty distributions, one below the 20th percentile and the other above. Modeled uncertainties ranged within a factor of 3–30. Mean modeled estimates for soil and dust ingestion are consistent with past information but lower than the central values recommended in the 2008 EPA *Child-Specific Exposure Factors Handbook*. This new modeling approach, which predicts soil and dust ingestion by pathway, source type, population group, geographic location, and other factors, offers a better characterization of exposures relevant to health risk assessments as compared to using a single value.

KEY WORDS: Children; dust ingestion; exposure modeling; SHEDS model; soil ingestion

1. INTRODUCTION

Soil and dust ingestion can be important exposure routes for environmental health risks. The 2008 U.S. EPA's *Child-Specific Exposure Factors Handbook*[(1)] describes in detail the various methodologies and relevant studies as part of developing recommended values for soil and dust (soil/dust) ingestion rates for children. However, the vast majority of information on soil/dust ingestion rate estimates reported in the literature and discussed in U.S. EPA 2008[(1)] are derived from trace element biomarker studies,[(2–12)] as opposed to physically-based process driven exposure modeling methodology described in this article. The research presented here has two main objectives. The primary objective is to demonstrate an application of EPA's

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Office of Research and Development (ORD), National Exposure Research Laboratory's (NERL) Stochastic Human Exposure and Dose Simulation Model for multimedia pollutants (SHEDS-Multimedia) to estimate soil and dust ingestion exposures of young children 3 to <6 years old. In particular, this approach is intended to identify and quantify the key factors contributing to the predicted variability and uncertainty in the soil and dust ingestion exposure estimates. The secondary objective is to compare and evaluate the dermal contact and incidental ingestion modules of the SHEDS-Multimedia (hereafter referred to as the SHEDS) model by comparison of modeled results to existing information from tracer-based field measurements. The two approaches that are now made available for characterizing soil and dust ingestion exposures differ considerably.

In tracer-element-based mass-balance studies, typical soil/dust ingestion estimates are based on tracer element concentrations measured in fecal output minus that in food divided by the concentration of the element in soil. Soil and duplicate food samples and information on tracers in vitamins and medicines are also collected for tracer element analyses. These studies often included three to four consecutive daily determinations each week over 2 weeks. Up to eight tracers have been considered by some investigators.[6,7] Typically, among the more reliable tracers used for this methodology were aluminum, silicon, yttrium, and zirconium. Manganese, titanium, vanadium, and barium were usually found to be less reliable. There have been few attempts to synthesize and interpret the results published by these earlier studies. In particular, two secondary analyses, conducted collaboratively with others by the first author of this article, explored statistical approaches to fit variability and uncertainty distributions to the published results.[13,14]

To model children's exposures to chlorpyrifos from incidental soil and dust ingestion pathways, Buck *et al.*[13] estimated age-dependent variability and uncertainty distributions for soil and dust ingestion rates (mg/day) based on a number of these key trace element studies. Briefly, the reported data for Al and Si geometric mean (GM) or median ingestion rates (25–60 mg/day) and mean of variances from Calabrese *et al.*,[6] Davis *et al.*,[5] and Thompson and Burmaster[8] were used by the Buck *et al.*[13] to estimate a geometric standard deviation (GSD) in fitting a lognormal distribution [Log N(GM, GSD]) of Log N (40.9, 3.6). The uncertainty distribution for the GM or the median was defined as an equal probability mixture of two normal distributions (M $\times$ N [mean # 1, *SD* # 1, mean # 2, *SD* # 2, probability of # 1 vs. # 2])—one for the Al tracer and one for the Si tracer (M $\times$ N [33.1, 6, 53.1, 6.6, 0.5]). A triangular uncertainty distribution (Tri [min, peak, max]) for the GSD was selected assuming that the estimated GSD is within the range fitted for either tracer in the three studies (Tri [2.2, 3.6, 6.5]).

Refined estimates of age-dependent distributions for soil/dust ingestion rates were presented in Zartarian *et al.*[14] In this analysis, Table II in Stanek and Calabrese[11] was used to develop a robust median estimate from the Amherst and Anaconda studies. The means (over the 2-week original study period) of the two median (over all elements within a day) values (17 mg/day and 45 mg/day) were averaged to estimate a representative median value of 31 mg/day as the GM for a lognormal soil/dust ingestion distribution. The GSDs for the assumed lognormal distributions were estimated from the medians (i.e., 17 mg/day and 45 mg/day) and the arithmetic means (i.e., 31 mg/day and 179 mg/day) also given in Table II in Stanek and Calabrese.[11] An average GSD of 4 was estimated based on the two GSD values of 3 and 5.3. Based on these estimated parameters, a lognormal soil/dust ingestion rate distribution [Log N (31, 4)] with an arithmetic mean of 81 mg/day was proposed, reflecting the considerable variation in both the protocols and results from the various field studies and tracer elements used. Subsequently, a bootstrap methodology was used to generate (GM, GSD) pairs to empirically describe the uncertainty surrounding the fitted soil/dust ingestion rate variability distribution.

We mention here a number of the key technical and methodological issues and challenges with using empirical tracer-based approaches to estimate soil/dust ingestion rates for children. U.S. EPA[1] discusses these and other issues more fully: uncertainties with transit time of food in the body; irregular fecal samples; intake and biological variations within a day; variations in dietary intake and composition within and between days; missing observations; negative values produced from applying a mass-balance model; recovery and stability issues with some tracers; other unaccounted sources of tracer intake; nondifferentiation of soil and dust intake; lack of representativeness of the study population; insufficiency of 2 weeks of data for estimating seasonal or annual average ingestion rates; modeling and statistical analysis complexities; lack of suitability of data for estimating ingestion rates for pica behavior children; expense and difficulty associated with implementing sample collection, analyses, and interpretation of results.

The focus of this article is an alternate approach to estimating soil and dust ingestion, i.e., using a probabilistic human-activity-based physical model SHEDS developed by EPA. Videography studies of children in everyday activities indoors and outdoors provide frequency and type of contact with different surfaces, objects, and body parts.[15,16] EPA's physically-based probabilistic SHEDS exposure model has taken the approach of combining diary information on sequential time spent in different locations and activities from EPA's Consolidated Human Activity Database (CHAD) (http://www.epa.gov/chadnet1), micro-activity data (e.g., hand-to-mouth frequency, hand-to-surface frequency), microenvironmental surface/object soil or dust loadings, and other exposure factors (e.g., soil-to-skin adherence, saliva removal efficiency).

The SHEDS-based physical modeling methodology described in this article for estimating soil and dust ingestion rates is an important contribution to the literature for the following reasons. Many of the chemical site-specific environmental exposure and risk assessments currently use for this key value either a screening level single point central estimate recommended in U.S. EPA 2008[1] or information extracted from limited number of earlier tracer-based studies that are based on measurements conducted in diverse geographical locations on children of different age groups with uncharacterized or unreported macro- or micro-activity status. On the other hand, the present methodology can be applied to children of specific age groups with matched age-appropriate activity and behavior profiles that are physically linked to locally and cohort relevant contact events with outdoor soil and anticipated indoor dust loadings. Consequently, the proposed model predicts a full variability distribution of incidental soil and dust ingestion rates for the target population, along with corresponding prediction uncertainties, derived from detailed characterization and quantification of key sources of input and model parameter uncertainties.

2. METHODS

The code used for estimating daily ingestion of soil and dust by children is functionally equivalent to that used in SHEDS-Multimedia model version 3 (http://www.epa.gov/heasd/products/sheds_multimedia/sheds_mm.html).[17,18] Certain changes to the input files (as discussed in Section 2.3) were made to focus on dust and soil, rather than on an applied chemical. For this assessment, it is assumed that "soil" and "dust" do not have any distinguishing chemical or physical properties from each other except representing contact with similar types of particles in different contact locations. Matter picked up outdoors is called "soil" and matter picked up indoors is called "dust."

2.1. SHEDS Modeling Method for Soil/Dust Ingestion

SHEDS generates simulated individuals who collectively match the population age-gender distribution. Each such individual is assigned a set of activity diaries drawn from EPA's CHAD human activity database[19] and is assigned other relevant modeling parameters by randomly sampling from input distributions. Each individual is then followed through time, generally up to 1 year, and the model computes changes to their exposure at the diary event level. These correspond to the events as delineated in CHAD, and range from 1 minute to 1 hour in duration. A year-long simulation will generally consist of 10,000 to 20,000 diary events. The SHEDS output allows calculation of within-person statistics (such as the average daily soil and dust ingestion), as well as across-person statistics (such as population percentiles).

Two methods are available in SHEDS for determining soil and dust ingestion. The "direct" method uses input variables for the rate at which soil is ingested (mg/h) while outdoors, and for the rate of dust ingestion (mg/h) while indoors and awake. Zartarian *et al.*[14] used the somewhat simpler direct approach. SHEDS can also use an "indirect" more mechanistic-based approach considered in this article, in which soil and dust first adhere to the hands, then the loading on the hands persists until washed off or otherwise removed, or else ingested by hand mouthing. SHEDS also permits soil and dust to adhere to the rest of the exposed (unclothed) skin on the body, but here it is assumed that transfer to the mouth can only occur for the hands. Thus, while body exposure to chemicals can lead to dermal absorption, that pathway is not relevant to the current application of the SHEDS model for estimating inert soil and dust ingestion rates. SHEDS also addresses the object-to-mouth pathway for soil/dust ingestion. Objects such as toys may be placed in the mouth or chewed, especially by very young children. The modeling approach assumed for mouthing of objects considers that objects that are subject to frequent play and mouthing (and possibly cleaning) may have less dust on them than, say, a typical carpet or floor.

SHEDS has a limit on dermal loading. Beyond a certain point, new exposures are assumed to be ineffective in increasing the loading. This then limits the amount available for transfer from the hands to the mouth. The overall ingestion rates may depend on the setting of the maximum dermal loading. There is a single variable for soil and dust combined, since there is no distinction made between the physical or chemical properties of soil and dust for mass purposes after it has been transferred onto the skin.

Using the current indirect modeling approach, SHEDS can estimate the soil and dust ingestion in a physical or mechanistic way. The amount ingested is a function of activity, time outdoors, environmental concentrations, soil-skin and dust-skin transfer, hand washing frequency and efficiency, hand-mouthing frequency, area of object or hand mouthed, mouthing removal rates, and other variables. For this analysis, estimates for the distributions of these exposure factors were obtained from the literature, and have been used in this SHEDS model application to predict estimates of soil and dust ingestion rates. The SHEDS model includes other input factors, related to chemical usage, chemical absorption, and variables for estimating dose and elimination rates. However, these are not relevant for purposes of determining soil and dust ingestion and thus set to zero for this soil/dust application.

2.2. SHEDS Modeling Equations

2.2.1. Accumulation Processes of Soil/Dust on Hands

The basic transfer equations to the hands are different between indoor (for dust) and outdoor (for soil) microenvironments. Indoors, the amount of dust present is measured as mass per unit surface area. For low levels (where the maximum dermal loading is less of a concern), the amount transferred is a fraction of the amount contacted. Thus, if 100 cm^2 of hand surface is pressed on the floor, a fraction of the dust in that 100 cm^2 of floor area may transfer to the hand. Outdoors, the amount of soil present is effectively unlimited. The relevant variable is not the amount of soil in the environment, but the amount of skin available to receive the soil. If 100 cm^2 of hand surface touches the ground, the amount of soil transferred to the hand depends on the soil-skin adherence, measured in units of (mg soil/cm^2 skin area). For this reason, indoor dust loadings are input to SHEDS, but outdoor soil concentrations are not.

2.2.1.1. Soil adherence on hands. SHEDS assumes that any time the simulated person is outdoors, the potential for dermal contact with soil exists. The diary times reported as either times spent in "outdoor-home" or "outdoor-other" microenvironments in CHAD are subject to soil contact by both hands. For purposes of determining ingestion, only hand-to-mouth contact is considered relevant. Contribution to soil ingestion via soil contact between the mouth and the rest of the body is not considered. On each outdoor event, new soil exposure is calculated as follows, based on Zartarian *et al.*:[18]

$$E_{\mathrm{soil},e} = \mathrm{Adh}\ A_{\mathrm{hands}}\ \mathrm{CR}_{\mathrm{hands},e}\ T_e,$$

where $E_{\mathrm{soil},e}$ is the new soil exposure for event e (mg/event), Adh is the soil-skin adherence factor (mg/cm^2), A_{hands} is the surface area of both hands (cm^2), $\mathrm{CR}_{\mathrm{hands},e}$ is the skin-soil contact rate (1/hour) for hands, and T_e is the event duration (hours/event).

Variables in this and subsequent equations are discussed in detail in the section on model input distributions. The new exposure from this diary event is added to the prior hand loading (the carryover from the previous diary event). As indicated below, adjustments are then made for maximum dermal loading, absorption, hand mouthing, and washing/bathing. These steps are repeated for every diary event.

2.2.1.2. Dust transfer to hands. For indoor diary events, dust may be transferred to hands at each new contact event. The equation for the new dust exposure is given below based on Zartarian *et al.*:[18]

$$E_{\mathrm{dust},e} = C_{\mathrm{dust},e} A_{\mathrm{hands}} \mathrm{CR}_{\mathrm{hands},e} \mathrm{TE}_{\mathrm{hands},e} T_e,$$

where $E_{\mathrm{dust},e}$ is the new dust exposure for event e (mg/event), $C_{\mathrm{dust,e}}$ is the dust concentration on contacted surface (mg/cm^2), A_{hands} is the surface area of both hands (cm^2), $\mathrm{CR}_{\mathrm{hands},e}$ is the skin-surface contact rate (1/hour) for hands, $\mathrm{TE}_{\mathrm{hands,e}}$ is the surface-to-hand transfer efficiency (–), and T_e is the event duration (hours/event).

2.2.2. Removal Processes of Soil/Dust on Hands

Due to carryover from prior events, whether the person is indoors or outdoors, there are likely to be nonzero loadings of both soil and dust on the hands at any time. Separate running totals are kept for each, but the sum of the two is subject to a maximum dermal loading check. If the total exceeds the limit, both components (soil and dust) are scaled back proportionally until the limit is reached but not exceeded.

The SHEDS model allows for dermal absorption from residues or particles on skin, depending on the properties of the target chemical being tracked. However, for purposes of estimating ingestion of soil and dust (as opposed to its chemical components) the dermal absorption rates are set to zero here. Soil may be removed by hand washing or bathing/showering. Hand washing events are added to the simulated individual's diary, since these are not reported in CHAD; bathing events are also added, as described below, if not reported by a CHAD individual for a given day.

2.2.2.1. Hand-to-mouth exposure transfer for soil or dust. Soil on the hands may be ingested via hand mouthing, as in the following equation modified from Zartarian *et al.*:[18]

$$E_{\mathrm{c,hm},e} = \mathrm{CE}_{\mathrm{c,h},e}\,(\mathrm{HF}_e/2)\,[1 - (1 - \mathrm{HMRE})^{(\mathrm{FQH}_e T_e)}],$$

where $E_{\mathrm{c,hm},e}$ is the new hand-to-mouth ingestion exposure for event e (ug/event) for category "c" (either soil or dust), $\mathrm{CE}_{\mathrm{c,h,e}}$ is the cumulative dermal hand loading for event e (ug) for category "c," HF_e is the fraction of one hand that enters the mouth (–), HMRE is the hand mouthing removal efficiency (fraction transferred to mouth) (–), FQH_e is the frequency of hand-mouth activity (mouthing events/hour), and T_e is the duration of diary event (hours/event).

The loading that enters the mouth is the hand loading times the fraction of hand area entering the mouth. The above equation includes division by two since the loading counts both hands whereas fractional area refers to one hand (e.g., 10% of one hand is 5% of both hands). For a single hand-mouth insertion, the amount removed would be this loading times the variable "HMRE," which measures the saliva removal efficiency for a hand mouthing event. For multiple insertions during the same diary event, it is assumed that the same part of the hand is mouthed repeatedly, and each mouthing removes the same fraction of the loading that remains from the prior insertion. It is relevant to calculate the amount remaining on the mouthed portion of the hand. If this amount starts at "load," then each successive mouthing multiplies this amount by (1 – HMRE), so after N mouthings the amount left on that part of the hand is load $(1 - \mathrm{HMRE})^N$. Here N is the number of hand mouthings in one diary event, which is given by the product of the hand-mouth contact frequency FQH (#/hour) and the event duration T (hour). This product may not be an integer. The amount transferred to the mouth is the difference between the starting and ending loadings on the hand, namely, (load–load $[1 - \mathrm{HMRE}]^N$). SHEDS uses different FQH distributions, depending both on age and whether the microenvironment is indoors or outdoors.

The above equation assumes that repeated hand mouthings during the same CHAD diary event all involve placing the same part of the hand into the mouth, and that no reloading (replenishment) of surface residues to the hands occurs within a diary event. Replenishment is assumed to occur at the beginning of each new CHAD diary event. More research is needed on the sensitivity of results to assumed replenishment times. At the end of each diary event, the mass remaining on the hands is redistributed evenly (effectively a reloading or replenishment process for the mouthed part of the hand). This allows more hand-to-mouth transfer on the subsequent diary event, even if the mouthed part has negligible loading remaining after the current event.

2.2.2.2. Hand washing/bathing adjustments. The dermal loading of soil and dust on the hands may be lessened or eliminated by hand washing or bathing (which includes showering and swimming). The CHAD diaries sometimes include showering/bathing as separate events, but often they are included implicitly in larger groupings such as dressing, personal care, getting ready for bed, and others. Depending on which CHAD diaries are assigned to a SHEDS individual, there may be regular bath/shower events or not. SHEDS uses a multinomial distribution for the maximum number of days between baths. This is sampled once per person. Whenever the diary assigned to that person reaches that duration without an explicit bath/shower event, SHEDS inserts one into the diary.

Hand washing is never reported as a separate diary event in CHAD. SHEDS therefore generates random hand-washing events that are added to the diary. The input to SHEDS is the distribution for the mean number of hand washings per day. This is sampled once per person, and serves as the basic behavioral tendency for that person. The actual number and timing of hand washes varies from day to day. As an example, suppose a SHEDS individual is assigned a mean of four hand washes per day. Since the average person is awake 16 hours per day, this corresponds to a 25% chance each hour for hand washing to occur, or equivalently, a 12.5% chance to occur during a typical 30-min diary event. Each event is checked randomly using a duration-weighted probability. Each day will be different, but on average this person will have about four hand-washing events per day. When either hand washing or bathing occurs, the hand loadings of both soil and dust are lowered according to the removal efficiency selected for the event:

$$\mathrm{CE}_{\mathrm{c,post},e} = \mathrm{CE}_{\mathrm{c,pre},e}(1 - \mathrm{RE}_{\mathrm{w}}),$$

where $\mathrm{CE}_{\mathrm{c,post},e}$ is the hand loading after washing for event *e,* for category c (dust or soil) (mg), $\mathrm{CE}_{\mathrm{c,pre},e}$ is the hand loading before washing for event *e,* for category c (dust or soil) (mg), and RE_{w} is the removal efficiency for washing type w (hand washing or bathing).

2.2.3. *Direct Ingestion of Dust from the Mouthing of Objects*

This is often called the object-mouth pathway, as distinguished from the hand-mouth pathway. In this case, it could more accurately be called the floor-object-mouth pathway, since there is an implied transfer (or at least a relationship) between the floor concentrations and those found on objects such as toys. This is the pathway of greatest uncertainty, as the variables are poorly characterized in the literature. The floor concentrations for dust are often taken from carpet samples. Objects mouthed by children typically include hard plastic or fabric items, such as toys, cups, or stuffed animals[20,21] and can vary by home, culture, or socioeconomic status. It is assumed that hard plastic will hold less dust than fabric, but will transfer it more efficiently to the mouth. The object-mouth pathway uses essentially the same logic as the hand-mouth pathway. In effect, the hand is simply a particular example of an object that is mouthed. The object has a starting dust concentration (loading) per unit area that is calculated using a ratio of object-to-floor dust loading drawn from a user-supplied distribution. Part of the surface area of the object enters the mouth, and the same area may be mouthed multiple times on each diary event. On subsequent events, one assumes either that a different object is mouthed, or a different part of the same object, or that the dust is replenished by intervening contact with the floor (for the model, these are equivalent). Like hand-to-mouth transfer, it is assumed only to take place while the child is awake. But unlike hand-to-mouth, object-to-mouth is assumed to only occur indoors. While outdoor play (for example, digging in sandboxes) may involve object-soil-mouth contacts, this behavior is relatively infrequent and so ignoring it may not appreciably influence the overall soil and dust ingestion rate estimates.

The equation for new exposure via object-mouth dust transfer is based on Zartarian *et al.*:[18]

$$E_{\mathrm{om},e} = C_{\mathrm{dust},e}\mathrm{OF}_{\mathrm{ratio}}\mathrm{OM}_{\mathrm{area}} \times [1 - (1 - \mathrm{OMRE})^{(\mathrm{FQO}_e T_e)}],$$

where $E_{\mathrm{om},e}$ is the new object-to-mouth dust ingestion exposure for event *e* (ug/event), $C_{\mathrm{dust,e}}$ is the dust concentration on floor (μg/cm^2), $\mathrm{OF}_{\mathrm{ratio}}$ is the object-to-floor dust concentration ratio (–), $\mathrm{OM}_{\mathrm{area}}$ is the object area entering the mouth (cm^2), OMRE is the object mouthing removal efficiency (fraction transferred to mouth) (–), FQO_e is the frequency of object-mouth activity (events/hour) (SHEDS uses age-dependent distributions), and T_e is the duration of diary event (hours/event).

2.3. Model Assumptions and Distributions for Input Variables

To run SHEDS, the user must specify (among other things) a simulation start date, a simulation length, simulation population size, and the ages to be simulated. The number of persons selected typically does not affect the results, other than giving tighter confidence intervals when larger numbers are run. A reasonable number for model stability is 1,000 persons. For this analysis we examined 3 to <6 year-old children only based on high frequency of mouthing behaviors for this age group and availability of more adequate exposure factor and input data for the SHEDS model than for some of the other age groups. The surface area of hands distribution was derived from analysis of the NHANES III height and weight data (as in Zartarian *et al.*[14]). In the absence of data, we assumed a 50% chance an individual contacts a bare floor versus a carpeted floor when they contact an indoor floor surface (note: the impact of this assumption on model results was separately tested later).

The following modifications were needed to address contact with dust and soil as opposed to an applied chemical. While SHEDS usually restricts exposure to home locations, for these runs dust was assumed to be present in all indoor and in-vehicle locations, while soil was present in all outdoor locations. The chemical concentrations were set to 100% of the soil mass when outdoors or 100% of the dust mass when indoors. The probability of being in “treated areas” was set to one, so all diary events (except for sleeping and bathing events) had the possibility of hand contact with either dust or soil.

Table I summarizes the selected values for the other model input variables relevant for estimating soil and dust ingestion. Various statistical distributions were fitted first to existing data on model parameters and inputs and the best fitting distributions among those were then chosen using different statistical measures and visual evaluations of model fit. “Sampling Rate” in the table tells how frequently the model samples the variable (e.g., once per person). The details of the information presented in Table I are described next.

2.3.1. Soil-Skin Adherence Rate

A lognormal distribution with a geometric mean of 0.11 mg/cm^2 and a geometric standard deviation of 2.0 was used in this analysis, taken from Zartarian *et al.*[14] This distribution was based on data from Holmes *et al.*[22] and Kissel *et al.*[23,24] findings. These measurement studies used the protocol of measuring the hand loading after a fairly lengthy time outdoors (7 hours or more for workers, and 2–4 hours of play time for children). Thus, there is concern that these rates apply to the total adherence rate for multiple contacts over a long duration, not for a single diary event. In SHEDS the amount of soil-skin transfer is proportional to the time outdoors, until the maximum dermal loading limit is reached.

2.3.2. Max Event Duration (min/event)

Diary events in CHAD represent time periods spent in one location performing one general activity. The maximum event duration is the upper limit on the duration of CHAD activities; it was set to 30 minutes (60 minutes is the default). For shorter events the actual CHAD duration is used. The main consequence of this setting is that replenishment of hand

Table I. Distributions Used for SHEDS Input Variables in Modeling Soil and Dust Ingestion Rates

Variable	Name	Units	Sampling Rate	Form	v1	v2	v3	Min	Max
Adh	Soil-skin adherence rate	mg/cm^2	Person	Lognormal	0.11	2.0	–	–	–
T_{max}	Max. diary event duration	min	[–]	Point	30	–	–	–	–
Cdust	Dust loading on bare floor	μg/cm^2	Person	Lognormal	42	2.8			
Cdust	Dust loading on carpeted floor	μg/cm^2	Person	Lognormal	780	2.9			
CR	Skin-soil/surface contact rate	1/hour	Person	Triangle	0	2.4	4.8	–	–
TE	Surface-hand dust transfer eff.	[–]	Day	Triangle	0.01	0.02	0.03	–	–
HF	Fraction hand mouthed/event	[–]	Person	Beta	3.7	25	–	–	–
FQHi	Hand-mouth freq. (Indoors)	events/hour	Person	Weibull	0.75	12.59			
FQHo	Hand-mouth freq.(Outdoors)	events/hour	Person	Weibull	0.55	5.53			
REb	Bath removal efficiency	[–]	Person	Uniform	0.9	1.0	–	–	–
REh	Handwash removal eff.	[–]	Person	Uniform	0.3	0.9	–	–	–
HMRE	Hand mouthing transfer eff.	[–]	Day	Beta	2	8	–	–	–
OMRE	Object-mouth transfer eff.	[–]	Day	Beta	2	8	–	–	–
FHW	Mean handwashes per day	#/day	Person	Lognormal	3.74	2.63	–	1	12
OF	Object-floor dust loading ratio	[–]	Person	Uniform	0	0.20	–	–	–
FQOi	Object-mouth freq. (Indoors)	events/hour	Person	Weibull	0.8	5.3			
FQOo	Object-mouth freq.(Outdoors)	events/hour	Person	Weibull	0.6	5.0			
OM	Area of object in mouth	cm^2	Hour	Exponential	1	10	–	–	50
B	Days between baths	days	Person	Multinomial [.75, .14, .07, .01, .01, .01, .01]					
Max	Max. dermal loading	μg/cm^2	Person	Uniform	6,000	8,000			

Notes: The columns headed v1, v2, and v3 indicate the parameters for the statistical distribution used for the given variable (“.” means not applicable). By distribution, these v1, v2, and v3 parameters are: lognormal–GM, GSD; triangle–min, peak, max; uniform–min, max; Weibull–shape, scale; beta–parameter in the exponent of “x,” parameter in the exponent of “$(1 - x)$” for $f(x)$, where $f(x)$ is the probability density function; exponential–min, mean. (See Section 2.3 for details regarding the basis for these exposure factors.)

loadings occurs once per diary event, so a smaller limit implies more frequent replenishment. The dermal contact rate averages about two touches per hour for all exposed skin, so a 30-minute replenishment time is considered reasonable. About 34% of nonsleeping events in CHAD are longer than 30 minutes and are therefore split into two shorter events (one of 30 minutes and the other of variable duration). After splitting, about 55% of nonsleeping events are exactly 30 minutes, while the remaining 45% have an average duration of 12.3 minutes.

2.3.3. Dust Loadings (g/m^2)

For bare floors, we used a lognormal (0.42, 2.8) dust loading based on Adgate *et al.*,[25] which reported dust loading measurements (in g/m^2) for samples collected in 216 homes ($N = 444$). From the same study we used a lognormal (7.8, 2.9) g/m^2 to carpet dust loadings based on $N = 376$ for vacuum samples from carpets. We assumed in SHEDS a probability of 0.5 for contacting bare floors versus carpeted floors. These numbers are consistent with more recent studies.[26]

2.3.4. Skin-to-Soil/Surface Contact Rate (1/hour)

For this variable we fit beta distributions to hand-to-playset contact information from videotapes of four 5–7 year-old children in the NHEXAS MN Children's Study[27] and hand-to-hard floor contacts/hr for left hand and right hand from Zartarian *et al.*[28] (a four-child study). For the model input we used beta (10, 2.5) for hand-to-surface contact rate per 20 minutes and beta (42,166) for body-to-surface contact rate per 20 minutes.

2.3.5. Surface-Hand Dust Transfer Efficiency

Cohen Hubal *et al.*[29] reported transfer efficiencies for riboflavin (not dust) after 1–7 sequential contacts, on both carpet and laminate, for different surface loadings, skin motion, and wet/dry skin. A review of available papers, including: Clothier;[30] Brouwer *et al.*;[31] Camann *et al.*;[32] Ivancic *et al.*;[33] Rodes *et al.*;[34] Edwards and Lioy;[35] Edwards and Lioy;[36] Lu and Fenske;[37] Cohen Hubal *et al.*;[38] Cohen Hubal *et al.*;[39] suggested low values for this variable, on the order of 1%. We selected a triangular distribution ranging from 1% to 3%. It is important to note that this factor in the model applies to each contact and not for multiple contacts.

2.3.6. Fraction Hand Mouthed per Event

A beta [3.7, 25] distribution from Zartarian *et al.*,[14] based on Leckie *et al.,*[40] data was used. For a hand of size 200 cm^2, this translates to a mean area of about 26 cm^2, or about $1^1/_2$ fingers for a child.

2.3.7. Hand-Mouth Frequency (Indoors)

Weibull distributions for indoor and outdoor hand-to-mouth frequency were developed in a meta-analysis conducted by Xue *et al.*[41]

2.3.8. Bathing Removal Efficiency

This represents the fraction of dermal soil/dust loading removed from the hands during a bath or shower. No suitable data sources have been identified yet. Here bathing removal is assumed to be very efficient with a uniform distribution of [0.90, 1.0].

2.3.9. Hand Washing Removal Efficiency

Hand washing occurs much more frequently than bathing, so it has more potential to reduce hand-to-mouth transfer. Unfortunately, like the bathing removal efficiency, no good data sources have been identified that are specific to soil and dust. Here, hand washing is assumed to be less efficient and more variable than bathing, based on its shorter duration. We chose a uniform distribution [0.3, 0.9].

2.3.10. Hand-to-Mouth Transfer Efficiency

This variable is also called the saliva removal efficiency. It represents the fraction of the loading entering the mouth (on the hand) that is removed from the hand and subsequently enters the gastrointestinal (GI) tract on a single hand insertion. It is important to note that this is not the fraction of "hand loading" transferred, since only a small part of one hand is usually inserted into the mouth. Also, the total mass transferred to the mouth during one diary event depends on the number of hand-mouth insertions in a nonlinear manner. It is possible that "soil" and "dust" may have different transfer efficiencies. However, both soil and dust cover a wide range of properties (e.g., wetness, stickiness), and it is difficult to establish a robust distribution for this variable.

Kissel *et al.*[42] presented results of a lab-based examination of hand-to-mouth transfer of soil from thumb sucking and finger mouthing. They found 0.101 and 0.159 transfer efficiency for the two activities, respectively. The protocol in this study involved covering more of the hand than was mouthed, but the efficiency is relative to the total hand loading. Therefore, the SHEDS numbers should be higher than reported in this study. Cohen Hubal *et al.*[29] indicate a mean transfer of about 0.16 for riboflavin powder. We assumed a beta (2, 8) distribution, which has a 5th percentile near 0.05 and a 95th percentile near 0.52, with a mean of 0.20.

2.3.11. Object-Mouth Transfer Efficiency

This is the saliva removal efficiency for small objects placed in the mouth, like plastic toys or parts of stuffed animals. Here the value would depend not only on the nature of the soil or dust, but also on the material being mouthed. The entire object-mouth pathway may be a significant part of the total dust ingestion, but like some of the other variables, this variable is not well characterized either. The default assumption made here is that object-mouth transfer efficiency is the same as the hand-mouth transfer efficiency, namely, a beta (2, 8) distribution.

2.3.12. Mean Handwashes per Day

This is a continuous variable used to set the probability of hand washing. A random check on hand washing is made on each diary event when the child is awake. Thus, the number of actual hand washes varies from day to day, as do the specific times when the washing occurs. An upper bound of 12 is desirable, otherwise for some children nearly every diary event becomes a hand washing event. If a child really washes his or her hands more than 12 times per day, then it is likely that multiple hand washings would fall into the same SHEDS diary event. SHEDS considers multiple washings during one event to be the same as a single washing. Therefore, this variable in essence represents mean number of diary events per day with hand washing. The hand washing frequency distribution used here is the same as used in Zartarian *et al.*[14] In this report, data from Tsang and Klepeis,[43] Freeman *et al.*,[27] and Kissel (personal communication)[44] were pooled to fit an overall lognormal distribution (with GM 3.74 and GSD 2.63) since a similar distribution and parameters were found among these various studies.

2.3.13. Object-Floor Dust Loading Ratio

It was difficult to determine the object-floor dust concentration ratio from published literature. Gurunathan *et al.*[45] suggest two values (2% and 70%), but the latter was based on atypical conditions. We assumed that 10% would be a more central value, so the distribution was chosen to be uniform from 0% to 20%.

2.3.14. Object-Mouth Frequency (Indoors)

We used the Weibull distributions developed for indoor and outdoor object-to-mouth frequency in a meta-analysis conducted by Xue *et al.*[46]

2.3.15. Area of Object in Mouth

Based on the area of hand mouthed by 2–5 year-olds as reported by Leckie *et al.*,[40] and the assumption that children mouth less area of objects than their hand, an exponential distribution with a minimum of 1, a mean of 10, and a maximum of 50 cm^2 was chosen. The maximum is comparable to the surface area of a ping-pong ball.

2.3.16. Days Between Baths

A multinomial distribution was fit using raw data from the bathing frequency Soil Contact Survey (SCS)-II study provided by Kissel[44] and assumed equally spaced baths throughout the week. This was converted to a multinomial set of probabilities for the allowable number of days between baths, ranging from 1 to 7. While the data would theoretically allow fractional days between baths, an integral number of days was preferable; else the model would dictate multiple baths per day and at odd hours of the day. Examination of the data by individual ages did not suggest a need for parceling this parameter very finely by age. The most common number of baths per week was 7 for warm climate conditions. To generate the days between baths, the number of baths per week was divided into 7 and the result (if not equal to 1.0) rounded up to the next highest integer with the tails of the observed probabilities being "smeared." The probabilities for this variable are shown in Table I. This distribution is multinomial (i.e., a probability vector for a set of discrete outcomes). The first number in the vector is the probability for the outcome to be 1 day, the second number is the probability for 2 days, and so on.

2.3.17. Maximum Dermal Loading

The maximum dermal loading of dust and soil functions as a cap on the amount the skin can carry.

Data from various studies[22–24,42,47] indicate that soil adherence seldom exceeds 10 mg/cm^2 of skin (unless the soil is mud). Each study suggested use of a log-normal distribution for the amount of soil loading on the skin. Based on the geometric means and standard deviations from these studies, a uniform distribution from 6 mg/cm^2 to 8 mg/cm^2 was chosen. This variable is expressed in units of ug/cm^2 in the model code, so the input distribution is set to a uniform from 6,000 μg/cm^2 to 8,000 μg/cm^2.

2.4. Sensitivity and Uncertainty Analyses

To assess the sensitivity of the model results to the different inputs, a modification of an approach described by Xue *et al.*[48] was applied. First, a baseline run was conducted with every input set to its median value, and a median ingestion rate (41.7 mg/day) was determined. Then additional variability runs were conducted, as follows. A selected input was changed to its 5th percentile value while leaving all other inputs at their median, and the model was rerun. Next the selected input was changed to its 95th percentile, again leaving every other input at its median, and a new run completed. The mean of the ingestion rate was extracted from both of these runs. The response to the new input was measured by the ratio of the mean ingestion rates for selected key percentiles, calculated from the simulated population size of 1,200, to each other and to the median value from the baseline run. This process was repeated over all inputs.

Uncertainty analysis for predicted soil and dust ingestion rates was implemented as described by Xue *et al.*[48] Briefly, the approach utilizes two-stage Monte Carlo sampling as follows. For each input, a set of its necessary parameter specifications (e.g., mean and standard deviation for a normal distribution) was chosen from an uncertainty distribution. Variable specific uncertainty distributions were produced by using the bootstrap simulation approach described in Xue *et al.*[48] Initially three different levels of uncertainty for each variable were assigned by setting the bootstrap simulation size (K) as 15, 10, or 5, depending on the amount of available and acceptable data. The model variables were classified into these three groups of "K" based on the amount of existing information, namely, those with a lot ($K = 15$), some ($K = 10$), or little ($K = 5$) amounts of available information. These values were then used to randomly sample either 15, 10, or 5 values from the parent distributions during the bootstrap simulation process for iteratively fitting similar distributions that are used to characterize the uncertainty associated with the parameters of the underlying parent data distributions.[48] Only the object and hand mouthing events per hour variables were considered to have sufficiently complete information (i.e., $K = 15$). Soil-skin adherence factor, dust loading on floor surfaces, dust-skin transfer efficiency, and maximum dermal loading variables were categorized as having some data ($K = 10$). The rest of the variables (e.g., object-floor dust loading ratio) were grouped as having few or little data ($K = 5$).

The two-stage SHEDS modeling methodology generates first a full suite of variability distributions, which are used for a model run of M simulated individuals. This entire process of generating the full suite of variability distributions from the uncertainty distributions is then repeated N times, thus generating N population distributions for the soil and dust ingestion rate. Uncertainty is then evaluated graphically as well as numerically. In this study we selected $N = 200$ and $M = 1{,}000$. Results are graphically displayed in two different ways (one showing the three selected variability cumulative distribution functions (CDFs) corresponding to those CDFs with median values at 5th, 50th, and 95th percentiles of the 200 uncertainty simulations (ranked by their medians) and the other showing the full population uncertainty distributions corresponding to the 5th, 50th, and 95th percentiles from each of the 200 uncertainty simulations.

3. RESULTS

Using the inputs listed above, the SHEDS model predicts a mean total soil and dust ingestion rate around 68 mg/day, with a 95th percentile of 224 mg/day for children 3 to <6 years of age (Table II). For soil ingestion only, the modeled mean is 41 mg/day and the modeled 95th percentile is 176 mg/day. For dust ingestion via hand-to-mouth, the modeled mean is 20 mg/day and the modeled 95th percentile is 74 mg/day. For dust ingestion via object-to-mouth, the modeled mean is 7 mg/day and the modeled 95th percentile is 27 mg/day. Results shown in Table II indicate that on average about 60% of total soil and dust ingestion is from soil ingestion, 30% from dust on hands, and 10% from dust on objects.

Fig. 1 presents the predicted distribution of both total and soil and dust ingestion rates from the three separate pathways (soil ingestion, dust ingestion

Table II. Predicted Soil and Dust Ingestion Rates (mg/day)

Pathway	*n*	Mean	*SD*	p5	p25	p50	p75	p95	p100
Dust ingestion from HM	1,000	19.80	36.54	0.60	3.37	8.39	21.29	73.74	649.28
Soil ingestion from HM	1,000	40.96	78.29	0.15	5.26	15.34	44.85	175.60	1367.37
Dust ingestion from OM	1,000	6.85	14.41	0.06	0.69	2.41	7.43	27.23	252.68
Total ingestion	1,000	67.61	90.62	4.86	16.80	37.75	83.18	224.02	1369.67

Note: HM is hand-to-mouth, OM is object-to-mouth.

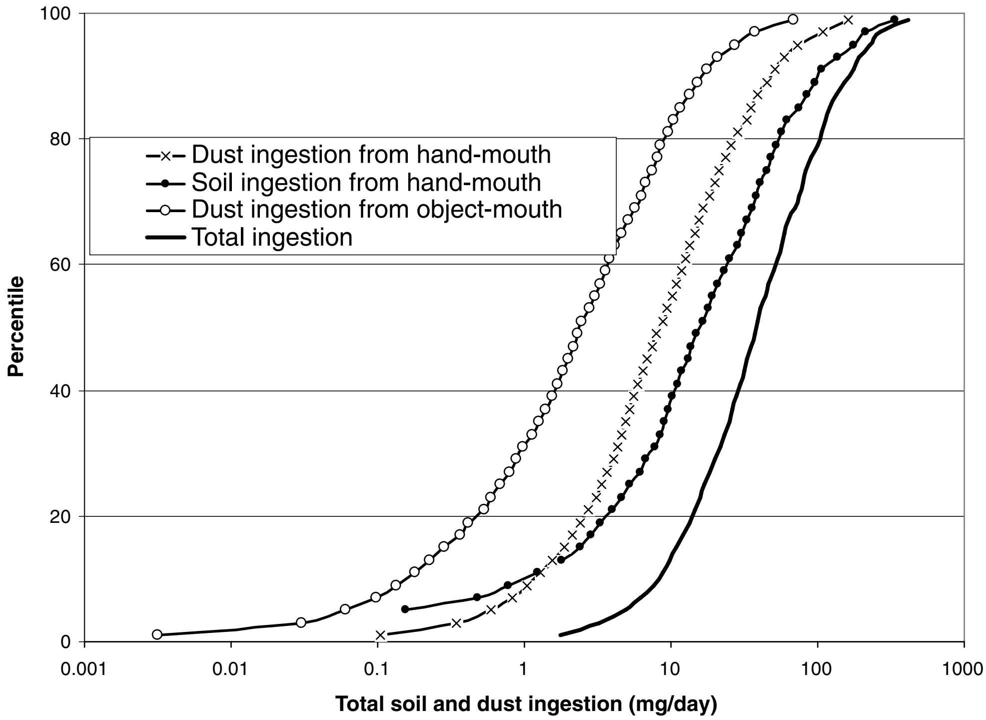

Fig. 1. Predicted distribution of soil and dust ingestion rates by pathway for 3–5 year-old children.

from hands, dust ingestion from objects). For most percentiles, hand-to-mouth soil ingestion was found to be the most important pathway, followed by hand-to-mouth dust ingestion, then object-to-mouth dust ingestion. The contribution to total soil/dust ingestion from soil only increases for the higher percentiles of the population.

3.1. Sensitivity Analyses

Table III summarizes the results from the sensitivity analysis of total and soil dust ingestion rate calculations. Examination of the ratios of predicted mean outputs for 95th percentile to 5th percentile, 50th percentile to 5th percentile, and 95th percentile to 50th percentile reveal that the model results (based on the typical ranking of the highest ratios of the various percentiles considered above the value of 1 and the inverse of the lowest ratios below the value of 1) are most sensitive to four variables: dust loadings on carpet and hard floor surfaces; soil-skin adherence factor; hand mouthing frequency; and mean number of hand washes per day. In addition, we conducted a separate sensitivity analysis to explore the sensitivity of results to the assumed fraction of carpeted floors (50%). We reran the model by choosing a greater percent of carpeted floor surface area (80% as opposed to 50%). This resulted in a 15% increase in the predicted total soil and dust ingestion rates (78 mg/day vs. 68 mg/day) and about a 45% increase in total dust only ingestion (39 mg/day vs. 27 mg/day).

Table III. Sensitivity Analyses for Modeled Soil and Dust Ingestion Values by SHEDS

Input Parameters	Soil + Dust Ingestion Means (mg/day)[a]		Ratio of Means		
	5th Percentile	95th Percentile	95th/5th	50th/5th	95th/50th[b]
Mean # hand washes/day per person	59	20	0.33	0.69	0.48
Removal efficiency during hand washing	51	37	0.73	0.81	0.90
Maximum dermal loading for hands	41	43	1.04	1.00	1.04
Object-mouth transfer efficiency	41	44	1.07	1.01	1.07
Object-floor concentration ratio	39	45	1.16	1.04	1.11
Object mouthing events per hour	39	46	1.19	1.07	1.12
Residue-skin transfer efficiency	38	47	1.21	1.07	1.13
Object surface area that enters mouth	39	47	1.21	1.05	1.15
Hand-surface contact rate	34	51	1.52	1.22	1.25
Removal efficiency during mouthing	15	66	4.56	2.82	1.61
Fraction of surface of one hand that enters mouth	19	72	3.88	2.21	1.76
Hand mouthing events per hour	5	85	17.51	8.49	2.06
Soil-skin adherence factor	23	104	4.47	1.77	2.52
Dust load	31	107	3.42	1.31	2.61

[a]The table reports the means ($n = 1{,}200$) from the sensitivity analysis runs with the input parameter in each row set to its indicated percentile in these two columns and all other parameters set to their medians.
[b]The table is ordered by these values.

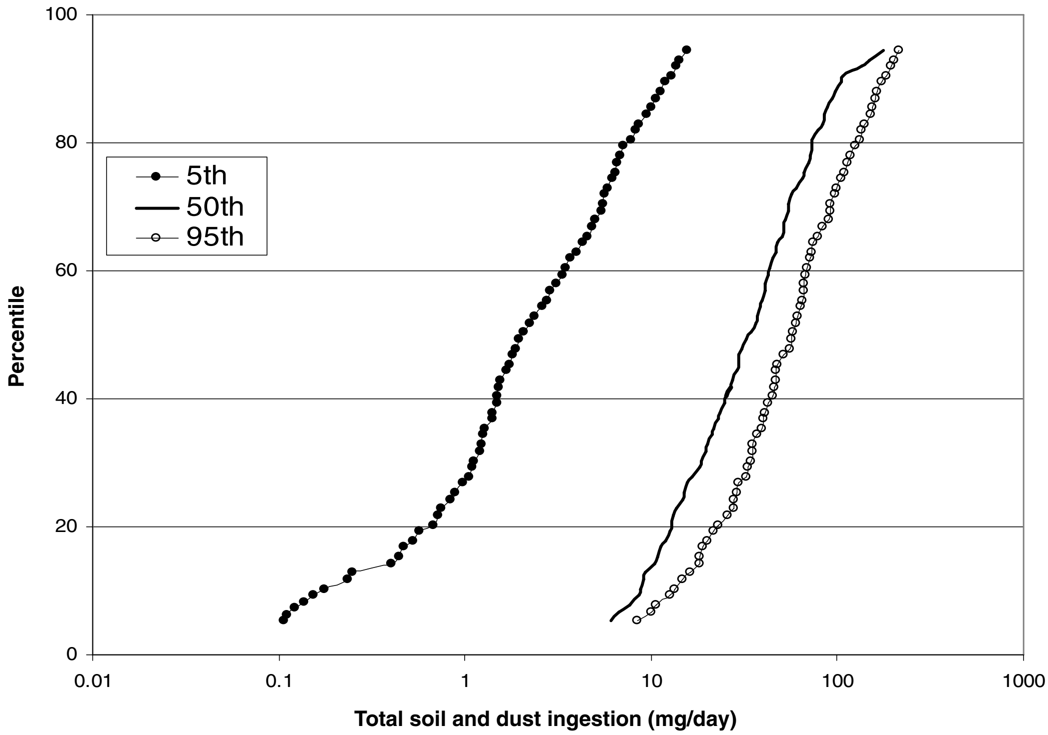

Fig. 2. Uncertainty CDFs for three selected variability percentiles for total soil and dust ingestion.

3.2. Uncertainty Analyses

Fig. 2 shows the uncertainty CDFs for three selected variability percentiles with 5th, 50th, and 95th percentile medians out of the 200 uncertainty simulations after they were ranked by their medians. The separation between these distributions represents the input and parameter uncertainty in modeling exposures. Fig. 2 indicates that the modeling uncertainties

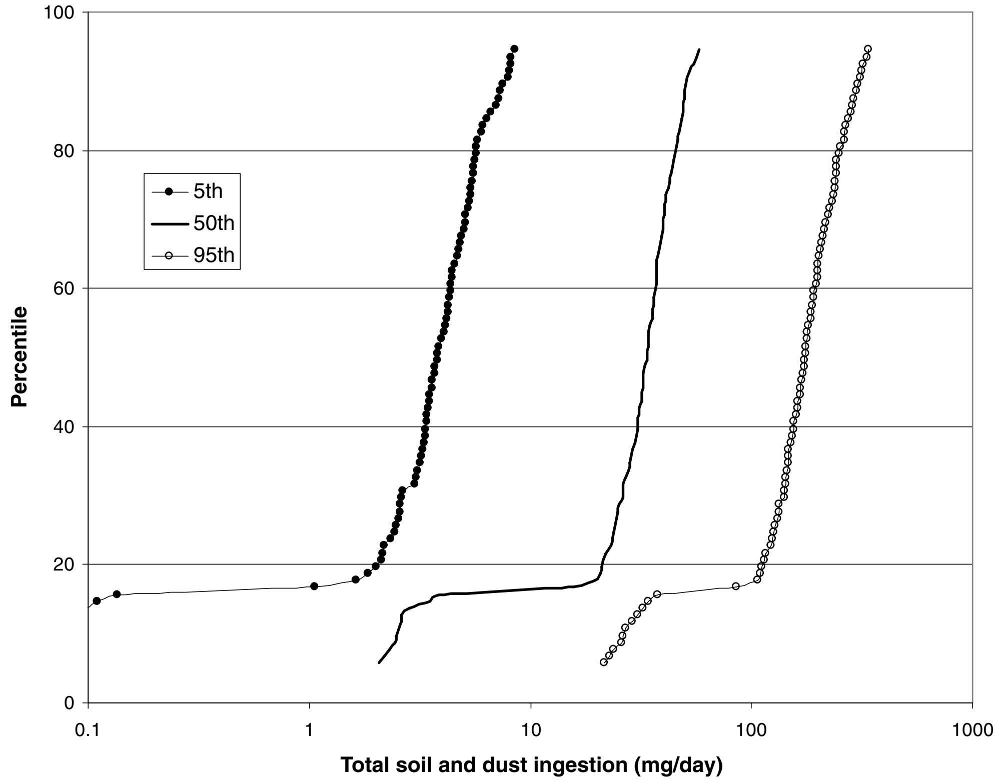

Fig. 3. Population uncertainty CDFs for total soil and dust ingestion.

are asymmetrically distributed around the 50th (median) or the central variability distribution. At the 50th percentile of these distributions the ratio between the 95th (median) percentile CDF and the 5th (median) percentile CDF is 28.2. At the 95th percentile of these distributions the ratio between the 95th (median) percentile CDF and the 5th (median) percentile CDF is 13.4.

Fig. 3 shows the uncertainty distribution associated with the 5th, 50th, and 95th percentiles based on 200 uncertainty simulations conducted. Noting the change from the 20th percentile to the 95th along the vertical axis, one finds that the 5th percentile changes by a factor of 4.1, the median by 2.7, and the 95th percentile by 3.0. However, changes are much greater if one were to calculate the change from the 5th percentile to the 95th percentile of these uncertainty CDFs (i.e., a change of factor of 243.4 for the 5th percentile, a factor of 28.3 for the median, and a factor of 15.8 for the 95th percentile).

4. DISCUSSION

This assessment focused on 3 to <6 year-olds, a key age group for hand and object mouthing behavior and for which sufficient information for exposure modeling exists. Since several inputs used in this modeling analysis were also age-dependent, we could not readily predict soil and dust ingestion rates of many other age groups mentioned in the U.S EPA 2006 guidance on selecting age groups for children.[49] Modeling soil and dust ingestion of other EPA recommended age groups using SHEDS could be a focus of future research. Based on our SHEDS-based physical modeling results, we found that the mean total ingestion of soil and dust is 68 mg/day; mean from soil ingestion is 41 mg/day; mean from hand-to-mouth dust ingestion is 20 mg/day; and mean from object-to-mouth dust ingestion is 7 mg/day. Our model-predicted estimates for soil and dust ingestion are in general consistent with existing literature values, but slightly lower than the central value (100 mg/day) recommended in the 2008 EPA *Child-Specific Exposure Factors Handbook*.[1] The average value of 100 mg/day falls between the 75th and 95th percentile for the 3 to <6 year-old age group simulated. The suggested upper bound value of greater than 400–1,000 mg/day (EPA 2008 *Child-Specific Exposure Factors Handbook*)[1] falls between the 95th and 100th percentile of modeled results.

The distribution of the predicted total soil and dust ingestion seemed to fit well a lognormal distribution with geometric mean = 35.7 and geometric standard deviation = 3.3. Interestingly, this lognormal distribution was somewhat similar to an empirical lognormal distribution (log N [31, 4]) previously fitted to the published tracer-element-based soil and dust ingestion rate data presented above and in Zartarian *et al.*[14] The concordance seen with model predictions and field-based tracer element soil and dust ingestion study results offers support to the validity of our modeling approach. A more in-depth comparison of our results to previously published studies individually, unfortunately, is not feasible at this time. This is due to important differences among the published study designs, such as random[5] versus nonrandom[9] selection of children, differences in climatic regions or soil/dust conditions across studies, and considerable variation in the age-groups chosen (often preschool children have been selected but specific age groups include both younger and older than the 3 to <6 year-olds focused in our work) and unreported details regarding time-activity or behavioral characteristics of these populations studied. Nevertheless, the general similarity of our results with the overall findings reported in the literature highlights the strengths of our modeling methodology and, in particular, its utility for identifying the key pathways and factors contributing to soil and dust ingestion rates by children of different age groups.

For most percentiles, predicted soil ingestion was the most important pathway, followed by hand-to-mouth dust ingestion, followed by object-to-mouth dust ingestion. The contribution to total soil and dust ingestion from soil only increased for the higher percentiles of the population. We were able to fit a lognormal distribution also to total dust ingestion rate predictions (Log N [11.9, 4.3]). A lognormal fit to the soil only ingestion rate data, however, failed due to skewness of the data, resulting in an unusually high geometric standard deviation. Sensitivity analyses revealed that the four most important variables contributing to variability in the predicted soil and dust ingestion values are dust loadings on carpet and hard floor surfaces, the soil-skin adherence factor, hand mouthing frequency, and the mean number of hand washes per day. A separate analysis conducted to explore the sensitivity of results to assumed fraction of carpeted floors (50%) indicated that choosing a greater percent of carpeted floor surface area (80% as opposed to 50%) resulted in a 15% increase in the predicted total soil and dust ingestion and about a 45% increase in total dust only ingestion. Clearly, this model input is quite influential on our results as well, and should be considered in future research.

The main limitations of this modeling-based assessment include few data for some of the input variables. Though there were relatively large data sets for the four most important variables identified through sensitivity analysis, data from new studies could be incorporated to improve the quality of input distributions used by SHEDS. The critical data needs for the model include collecting, processing, and incorporating more complete and representative behavioral and exposure factors data in future modeling-based analysis. For instance, additional information on the activities and environments of younger age groups (e.g., below 1 year-olds) and children with high hand-mouth, object-to-mouth, and pica behaviors are desirable. Information on soil or dust to skin adherence for broader groups of children, and indoor dust loadings on different types of objects mouthed (e.g., for different ages or cultures) and on floors in different locations and seasons inside homes with diverse characteristics (e.g., fraction carpeted versus smooth floors and how much contact children have with those surfaces) would be quite valuable for reducing uncertainties in model inputs or parameters. Recognizing that all these variables may differ across cultures or socioeconomic groups, future data collection efforts should recognize this point, both from the standpoints of modeling these subpopulations and ensuring that variability in the overall population is adequately characterized.

Despite these caveats and known limitations, the SHEDS results for soil and dust ingestion predictions for 3 to <6 year-old children are reasonable based on earlier research. The consistency of the SHEDS predictions with tracer-based field study results adds confidence to the model's capability for reliably predicting children's exposures to particles or particle-bound residues through the dermal contact route and hand-to-mouth and object-to-mouth ingestion pathways. One of the key advantages of this modeling approach is that it allows us to separate contributions from soil and dust, and from dust contributions from hand versus objects. Such information is useful for human exposure modelers simulating indoor and outdoor exposures. A physical approach to predicting soil and dust ingestion rates also allows the possibility of predicting incidental ingestion of soil and dust for specific age or population groups and geographic climates zones (e.g., older children, autistic children with greater hand-mouth activity; seasonal differences in activity and behavior; homes with higher dust loading and carpeting; children who spend more time outdoors in play grounds or daycares; children living in cold vs. warm or dry vs. wet climate zones). Since soil and dust ingestion rate values are often used in site-specific risk assessments (for either or both to outdoor exposures to soil or indoor exposures to dust), we believe that a modeling-based approach as presented here may provide a more quantitative and reliable estimate of the full range of incidental exposures to soil and dust (thus, not relying only upon a single central value that is typically done). Furthermore, as opposed to using the summary data from the literature or tracer-based studies, application of a stochastic model such as SHEDS for case-specific soil/dust ingestion predictions can provide valuable variability and uncertainty information for each population of concern that is essential for conducting a more robust risk and cost benefit analysis (cf. Özkaynak *et al.*[50]). Incorporating variability and uncertainty surrounding the exposure estimates is critical to making sound decisions and maximizing the benefits attained from such decisions.[50] For instance, superfund site and soil clean-up decisions typically consider likely impacts of alternative risk management or exposure mitigation choices by examining chemical exposure or risk trade-off options in comparison to risk benchmarks. While this article provides a general soil and dust ingestion rate prediction methodology, this modeling-based approach may also be used for chemical-specific analyses when contaminants are predominantly soil or dust bound, such as in the case of some metals, organics, and pesticides (see, for example, a recent report by Glen *et al.*,[51] describing the residential soil and dust exposure modeling of children 3–5 years-old to permethrin pesticides using the SHEDS-Multimedia Model:Residential Module, Version 4).

The SHEDS modeling approach is well suited to aid site or population-specific investigations since a full distribution of predicted soil and dust ingestion values with associated uncertainties may better inform these evaluations rather than relying on a single central value. In particular, modeled information can be used to perform an enhanced exposure and risk analysis for vulnerable subgroups that may be more highly exposed or sensitive than the rest of the study population. Moreover, the model predictions can further inform both risk assessment and risk management decisions by identification of critical factors or information elements contributing most to predicted exposures and risk. This type of detailed information will also guide future research activities to design collection of new information on the most important inputs. Finally, we recommend conducting method evaluation studies in the future, whereby both tracer-based field studies and physical model-based estimates are done and compared together using identical cohorts of children and environmental conditions, to better ascertain the strengths and limitations of both these approaches.

ACKNOWLEDGMENTS

We are grateful to our colleagues Jacqueline Moya (EPA/ORD/NCEA), Marian Olsen (EPA/Region 2), and Nicolle Tulve (EPA/ORD/NERL) for their helpful review and comments on the draft article.

DISCLAIMER

The U.S. Environmental Protection Agency through its Office of Research and Development partially funded the research described here under contract number EP-D-05-065 to Alion Science and Technology, Inc. It has been subjected to Agency review and approved for publication.

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